

Evaluating the extent to which wildfire history can be interpreted from inertinite distribution in coal pillars: An example from the Late Permian, Kuznetsk Basin, Russia

V. Hudspith ^{a,*}, A.C. Scott ^a, M.E. Collinson ^a, N. Pronina ^b, T. Beeley ^c

^a Department of Earth Sciences, Royal Holloway University of London, Egham, Surrey TW20 0EX, UK

^b Geology Department, Moscow State University, Vorobyovy Gory, 119992 Moscow, Russia

^c Fuels and Combustion, RWE Npower, Windmill Hill Business Park, Whitehill Way, Swindon, Wiltshire SN5 6PB, UK

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ABSTRACT

Inertinite (charcoal) distributions in two randomly sampled *in situ* coal pillars (seams 78 and 88) from the Late Permian Kuznetsk Basin, Siberia, were analysed using petrographic techniques to determine palaeowildfire histories (fire occurrence, type and return interval). *In situ* coal pillars are judged to be essential for this type of research as they retain information on the original inertinite distribution and maceral clast size ranges which can never be obtained from the crushed coals typically used for petrographic analysis.

The seams represent an ombrotrophic mire (seam 78) and mire with mire lake (seam 88) depositional settings but both environments show the same pattern of fire history. Charcoal is present in all lithotype units in both pillars. Both pillars contain episodic charcoal horizons representing local surface fires within the peat-forming environment, interspersed with frequent regional background fire events (as shown by small scattered inertinite).

This paper presents an approach to calculating fire return intervals (FRI) in these coal pillars by removing the thickness of less compactable charcoal horizons before calculating original duration of peat formation. This is achieved by using a range of peat accumulation rates and peat to coal compaction ratios. Resultant mean FRI ranges from 7 years (extremes 0.5 to 143 years), for a lithotype unit containing 4 horizons, to 70 years (extremes 5 to 1550 years), for a lithotype unit with 2 horizons. The mid-range values both suggest shorter fire return intervals than seen in modern peat-forming environments.

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1. Introduction

Wildfire is an important element of the Earth System (Bowman et al., 2009) not only in the modern record but since at least the Late Silurian (Glasspool et al., 2004; Scott, 2000). Charcoal produced during wildfires may be less biodegradable (Ascough et al., 2011) than uncharred material and therefore more likely to be preserved in the fossil record (Scott, 2010). We consider that all inertinite is charcoal (Bustin and Guo, 1999; Glasspool and Scott, 2010; Scott, 2010; Scott and Glasspool, 2007) though Hower et al. (2011) argue that some macrinite may have been formed through the activity of fungi and bacteria.

Inertinite contents in Permian coals vary from 3.9% to 83% but the overall mean value is high, 44% for the Early Permian (280 Ma) and 38.9% for the Changhsingian (all mineral matter free (mmf) basis) suggesting more frequent, widespread wildfire events which is hypothesised to be related to modelled high atmospheric oxygen levels

during the Permian (Glasspool and Scott, 2010). These values are much higher than peats formed under present atmospheric oxygen levels (mean inertinite of 4.3%) (Glasspool and Scott, 2010).

Inertinite distribution in coal can be used to interpret detailed palaeowildfire history at a local scale. There are three wildfire types; surface, crown and ground fires (as summarised by Davis, 1959; Pyne et al., 1996; Scott, 1989a). Horizons of macroscopic (>1 mm *sensu* Scott, 2010) fusinite and semifusinite are likely to represent local surface fires within the peat-forming environment, with limited transport history (Blackford, 2000; Clark, 1988; Clark and Royall, 1995; Tinner et al., 1998; Tolonen, 1983) whereas scattered microscopic charcoal (<180 µm, but often <20 µm) represents a windborne size fraction from regional fire events within 20–100 km of the fire source (Clark et al., 1998; Collinson et al., 2007; Conedara et al., 2009; Lynch et al., 2004; Ohlson and Tryterud, 2000; Peters and Higuera, 2007; Pitkänen et al., 1999). However, certain conditions, such as severe convection in high intensity crown fires and favourable topography, can sometimes carry centimetre sized charcoal particles several kilometres (Pisarcic, 2002; Tinner et al., 2006).

In this paper we present comparative petrographic data from two Late Permian *in situ* coal pillars (seams 78 and 88) from the Kuznetsk

* Corresponding author.

E-mail address: v.hudspith@es.rhul.ac.uk (V. Hudspith).

Basin, Siberia. Previous petrographic work (Pakh and Artser, 2003) reported that seam 78 had the highest inertinite content but this was only based on crushed samples representing a bulk seam sample.

Unlike crushed coals, *in situ* coal pillars retain the original spatial and temporal context of inertinite distribution and will therefore enable interpretation of local scale, Late Permian wildfire history.

2. Materials and methods

2.1. Sampling locality

The Kuznetsk Basin is located in South Western Siberia and has an area of 26,000 km² (Evtushenko et al., 1975) (Fig. 1A). Basin fill consists of 5 km of Permian non-marine siliciclastics and high volatile bituminous coals, grouped into three facies associations; fluvial channel-belt, overbank and floodplain/floodplain pond with extensive, long lived, mire environments on the floodplain (Davies et al., 2010).

Seams 78 and 88 are part of the Tailuganskaya Formation (Fig. 1B) which contains the thickest and most economic seams in the Kuznetsk Basin. Based on crushed coal industry data, seam 78 also has the highest inertinite content of the sequence (Evtushenko et al., 1975; Pakh and Artser, 2003).

Two *in situ* coal pillars were randomly sampled from two open cast mines (not named by request of the mine owners) that both exploit bituminous coals from the Late Permian. Seams were often in excess of 10 m thick (Fig. 2A) and coal pillar size in relation to total seam thickness is demonstrated in Fig. 2B(i), Fig. 2B(ii) (seam 78) and 2C (seam 88). It is outside the scope of this paper to analyse the entire seams, therefore for this study random samples were taken from accessible locations in each seam.

2.2. Dating the Permian sequence

The terrestrial Permian sequence is dated by traditional Russian correlation using a biostratigraphic framework which incorporates floral, ostracode, conchostracan, bivalve and charophyte assemblages (Mogutcheva and Krugovikh, 2009). The Latest Permian has been dated by Ar–Ar age determination of two basalt flows (250.3 ± 0.7 Ma and 250.7 ± 0.6 Ma) (Davies et al., 2010; Reichow et al., 2009). The basalt flows are above the latest coal seams (Davies et al., 2010) therefore the seams in this study must be older than the basalt flows.

2.3. Study methods

In situ coal pillars were removed from the coal seam face (Fig. 2B(ii); Fig. 2C) and wrapped tightly in aluminium foil to retain integrity and orientation. They were then transported in bubble wrap to prevent breakage.

The two coal pillars were embedded in plaster of Paris to retain integrity during cutting. The pillar was then cut in half. One half was embedded in polyester resin (1% hardener to 99% resin), cut into blocks of manageable size, milled and polished.

Petrographic analysis was undertaken on polished blocks, under oil using a Leica DM 2500 P reflectance microscope using a $\times 20$ objective. Representative colour photographs (2560×1920 pixel resolution) were taken using a 5 megapixel camera attached to the reflectance microscope and Prog-Res Capture Pro 2.7 software. Images were taken using the same lamp setting to ensure consistency and have not been post-processed in any way.

There is currently no standardised methodology for petrographic analysis of *in situ* coal pillars (Stach, 1982) although, approaches to

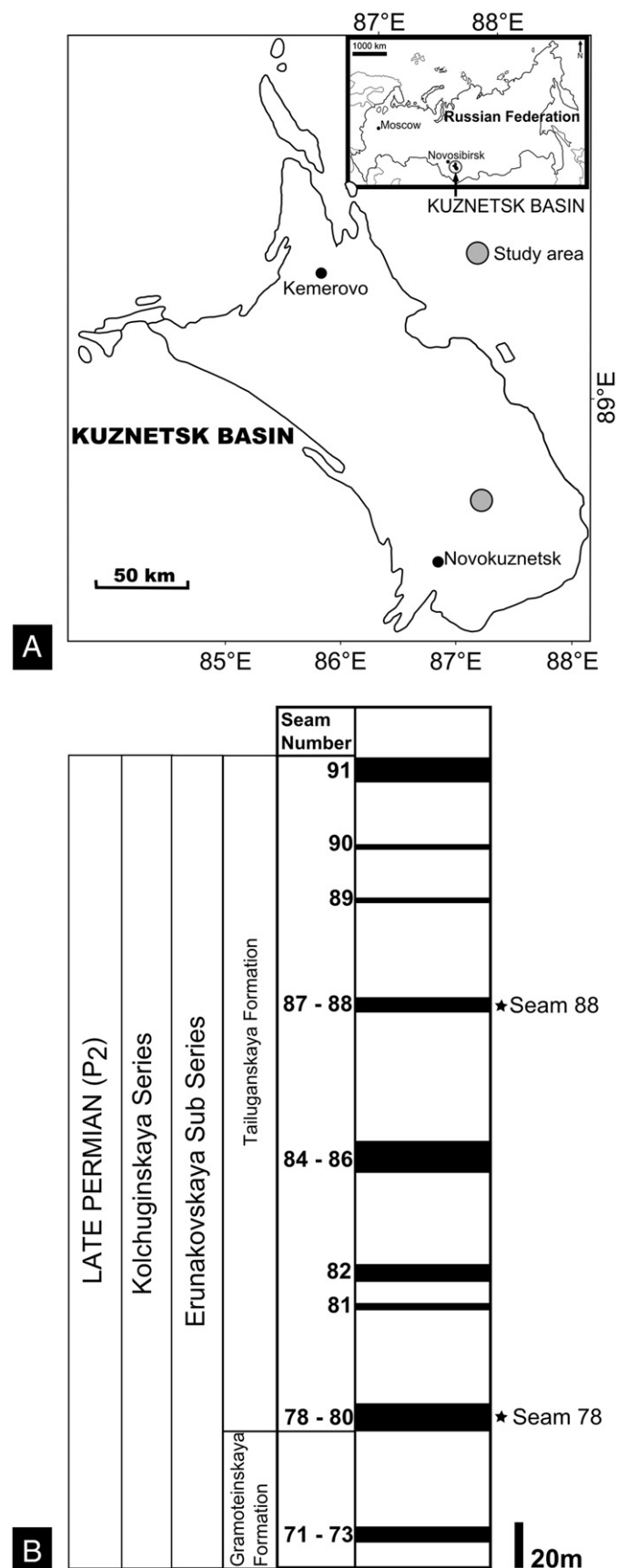


Fig. 1. A = Outline map of the Kuznetsk Basin showing the study area (after Pakh and Artser, 2003) with a small inset map showing the geographical context of the Kuznetsk Basin in Russia (after Walker, 2000). B = Schematic representation of relative coal seam and inter bed thicknesses obtained from borehole data from one of the open cast mines. The seams studied are marked with an asterisk (redrawn from Siberian mine company copy).

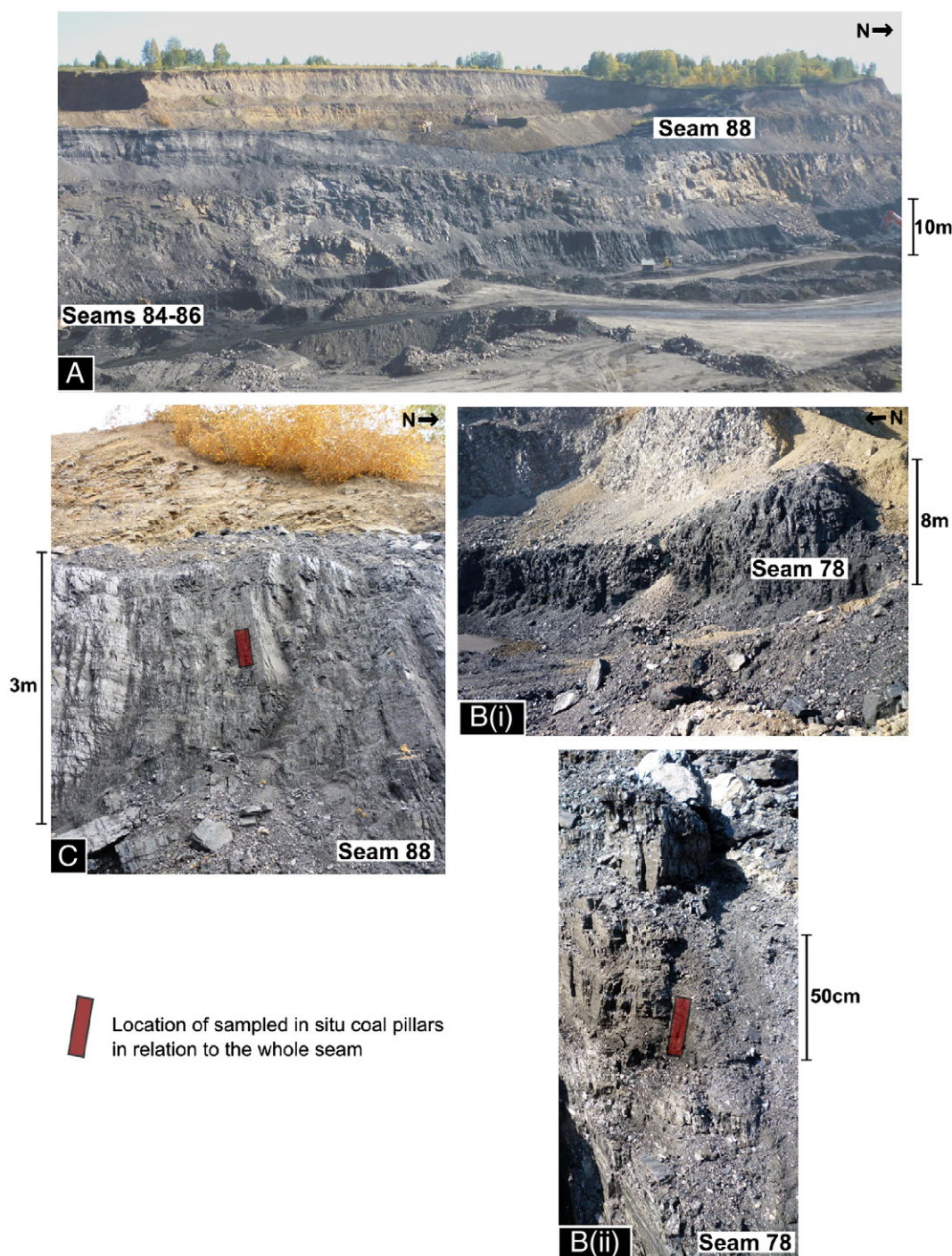


Fig. 2. A = General view of some coal seams from the opencast mine to show seam position and typical seam thicknesses. B(i) = Field photograph of seam 78 and B(ii) = field photograph showing seam 78 with position of the sampled *in situ* coal pillar. C = Field photograph of seam 88 with position of sampled *in situ* coal pillar.

developing a methodology have been attempted by several workers (e.g. Belcher et al., 2003; Collinson et al., 2007; Glasspool, 2000, 2003).

The two pillars were initially divided into visually distinct lithotype units (hereafter LU) (Figs. 3 and 4). The industry standard (BS 6127–3, 1995) Kötter graticule was used and three equally spaced vertical transects made perpendicular to bedding through each lithotype unit with a vertical step length of 1 field of view (FOV) (425 μm). One graticule (20 points) was counted every field of view. A point was counted when a maceral lay on the intersection of the graticule. Intersections on embedding resin were not counted. For each lithotype unit the petrographic data for all three transects were

added together to give a mean value for each lithotype unit and presented to a mineral included basis (Fig. 5). In order to compare these data to previous published work, inertinite contents were converted to mineral free (mmf) basis (Figs. 3 and 4). A pillar average for inertinite (mmf basis) was calculated by summing all point count data (all lithotype units) along the entire length of the pillar for the three transects to obtain a mean value per transect. The standard deviation (st. dev.) of the transect means is also given in the text in brackets after the pillar mean value and shown in Table 1. The pillar average also accounts for the lateral variability in lithotype unit thickness across the block. Maceral groups were identified using ICCP

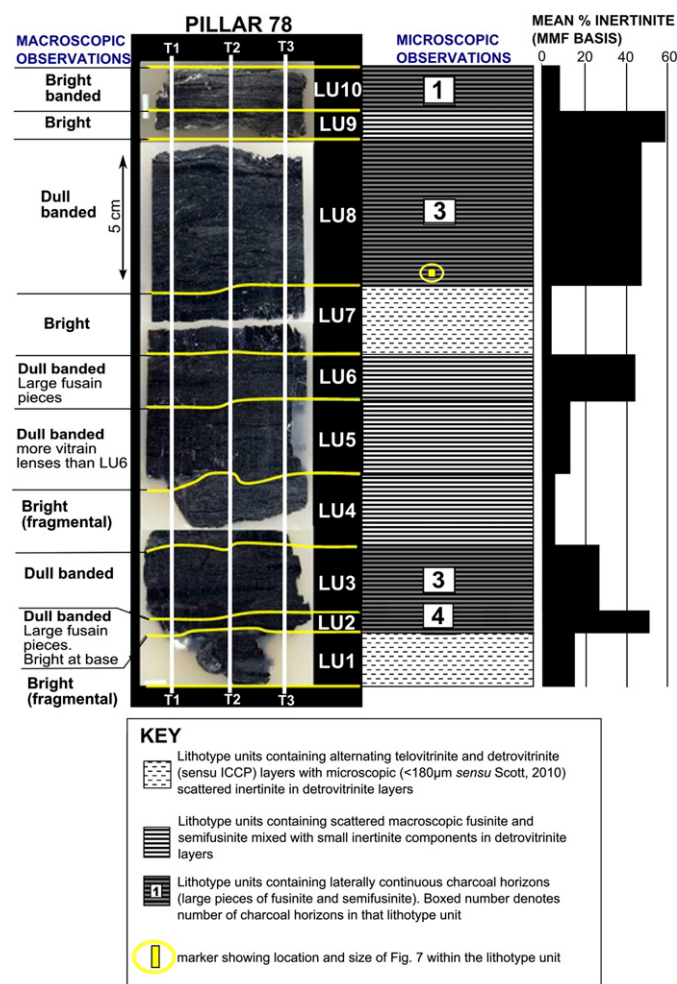


Fig. 3. Annotated schematic summary diagram of inertinite distribution in pillar 78 (compare with Fig. 4). The macroscopic appearance of the coal (image and annotations on left) is linked to microscopic representation of charcoal occurrence (patterned boxes on the mid right). The bar chart on the far right shows petrographic data (mean inertinite content) for each lithotype unit (reported to a mineral free basis, mmf).

schemes (ICCP, 1998, 2001). Therefore, fusinite and semifusinite macerals were identified based on qualitative reflectance, not measured. Charcoal horizons were identified based on a) lateral continuity of occurrence of charcoal clasts across the width of the block, b) clast size (pieces ≥ 1 FOV (425 µm) and c) discrete clasts of varying shapes and sizes.

Determination of sulphur content of the two coal pillars was carried out at the RWE Npower Fuel Characterisation Laboratory Facility in Swindon using the British standard procedure (BS, 1016–106.4.2, 1996). The sample weight of the lithotype units was too small to enable analysis of ash content at the RWE Npower facility so samples were sent to the Kentucky Center for Applied Energy Research and analysed according to standard ASTM techniques (ASTM Standard D5142-04, 2004). Sulphur data are reported to a dry ash free (daf) basis and ash data are reported to a dry (d) basis (Table 2).

X-Ray Diffraction was undertaken on pillar 88 LU2, LU4, LU6 and pillar 78 LU5 in order to confirm the composition of ‘mineral matter’ identified by petrographic analysis. The samples were analysed by D. Alderton at Royal Holloway, University of London. The pulverised coal samples were ground manually using an agate pestle and mortar with a small amount of water. A thin film of coal was then smeared onto a glass slide and dried in an oven at 40 °C. X-Ray Diffraction was undertaken on a Philips PW1710/1830 X-ray spectrometer using

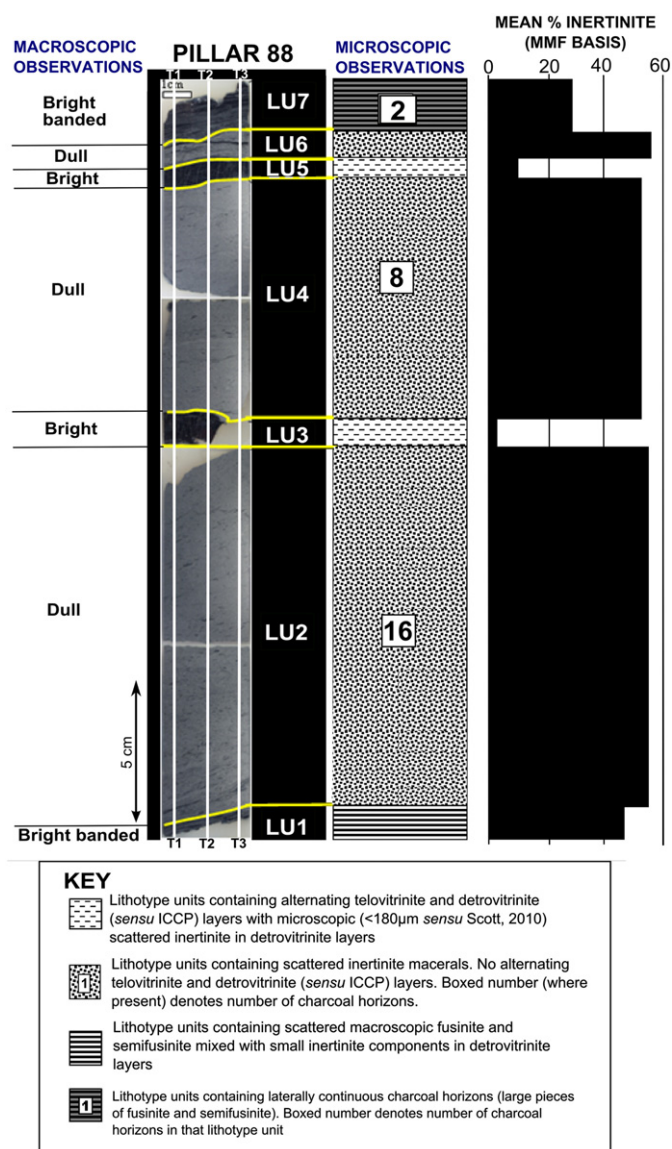


Fig. 4. Annotated schematic summary diagram of inertinite distribution in pillar 88 (compare with Fig. 3). The macroscopic appearance of the coal (image and annotations on left) is linked to microscopic representation of charcoal occurrence (patterned boxes on the mid right). The bar chart on the far right shows petrographic data (mean inertinite content) for each lithotype unit (reported to a mineral free basis, mmf).

Cu K α radiation. The samples were run from 4° to 60° (2 θ) at a rate of 1° per minute. Diffraction traces were produced using GBC Scientific equip. Pty. Ltd Traces (v.6) software. Intensity peaks on the resulting traces were identified and allocated to different minerals using the ICDD (International Centre Diffraction Data) mineral powder diffraction file.

3. Results

3.1. Characterisation analysis of pillars 78 and 88

All lithotype units in both pillars have low total sulphur contents (<1.3% daf basis) (Table 2). Pillar 78 has <7.5% ash content (d basis) for all lithotype units (<7.3% mineral matter) whereas pillar 88 ranges from 7% ash (LU3; 1% mineral matter) to 21% (LU4; 22% mineral matter). The majority of the mineral matter in these pillars is either quartz or kaolinite (determined by XRD). Quartz is inert during high temperature ashing (Gluskoter, 1975) which may explain why

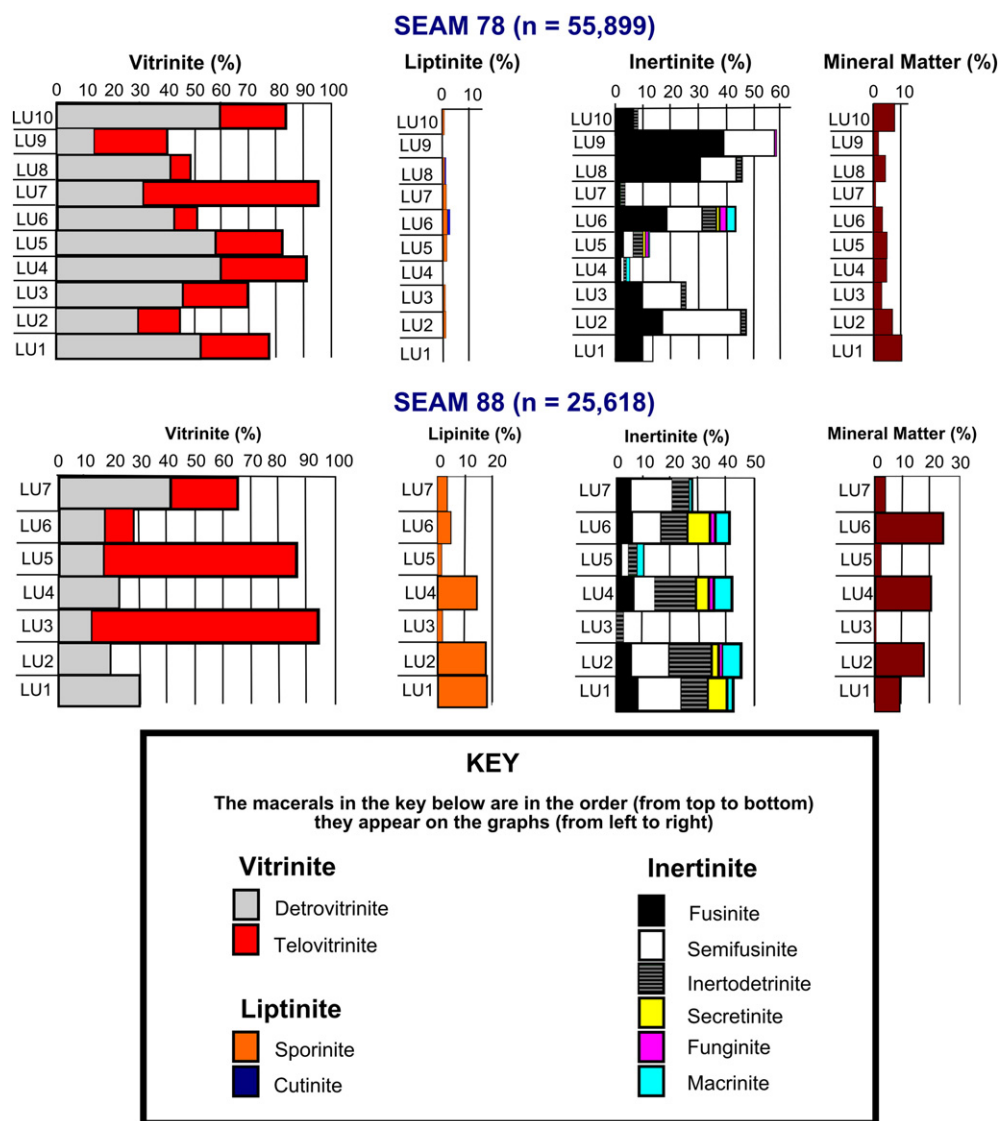


Fig. 5. Comparative stacked histograms of petrographic data from pillars 78 (top) and 88 (bottom) to a mineral included basis. The value next to the pillar name corresponds to the total number of points counted for that pillar (both organic and inorganic).

the ash and point count mineral matter values are comparable. Furthermore, the lithotype units in pillar 88 with high ash contents also petrographically contain higher liptinite contents (88LU2, 14%; Fig. 5) than pillar 78 (0–2%; Fig. 5).

3.2. Inertinite distribution and abundance within pillar 78

The 78 pillar can be divided macroscopically into ten visually distinct lithotype units (Fig. 3). These are subdivided using the

Table 1

Summary table of mean inertinite petrographic data for each transect (position of transects on each coal pillar shown in Figs. 3 and 4) and the standard deviation of the transect means for both pillars.

Coal seam	Transect number	Mean % inertinite (mmf basis)	Standard deviation of all transect means
78	1	26.26	1.25
	2	28.75	
	3	27.69	
88	1	45.88	2.34
	2	47.66	
	3	50.52	

descriptive scheme by Diessel (1965) into, bright (LU1, LU4, LU7 and LU9), dull banded (LU2, LU3, LU5, LU6, and LU8) or bright banded (LU10). Two of the bright vitrain rich lithotype

Table 2

Characterisation analysis results for sulphur (reported to a daf basis) and ash contents (d basis) of all lithotype units from pillars 78 and 88.

Sample name	Ash (%) (d basis)	Total sulphur (%) (daf basis)
78 LU1	4.24	1.27
78 LU2	3.32	0.91
78 LU3	3.66	0.84
78 LU4	7.51	0.96
78 LU5	3.92	0.77
78 LU6	3.24	0.7
78 LU7	2.25	0.84
78 LU8	5.35	0.84
78 LU9	5.08	1.06
78 LU10	4.67	0.84
88 LU1	13.13	0.23
88 LU2	18.77	0.22
88 LU3	7.16	0.25
88 LU4	20.89	0.24
88 LU5	9.68	0.24
88 LU6	19.81	0.21
88 LU7	17.58	0.21

units (LU1 and LU4) are also brittle and therefore fragmental in appearance.

Petrographic results from the lithotype unit analysis are illustrated in Fig. 5. Inertinite is present in varying abundances throughout the

coal pillar, ranging from 3% to 59% in different lithotype units (Fig. 5), with a pillar average of 29.8% mmf basis (st. dev. = 1.3; Table 1). The microscopic variations in inertinite distribution between lithotype units show repetition and can be subdivided into three categories, with all

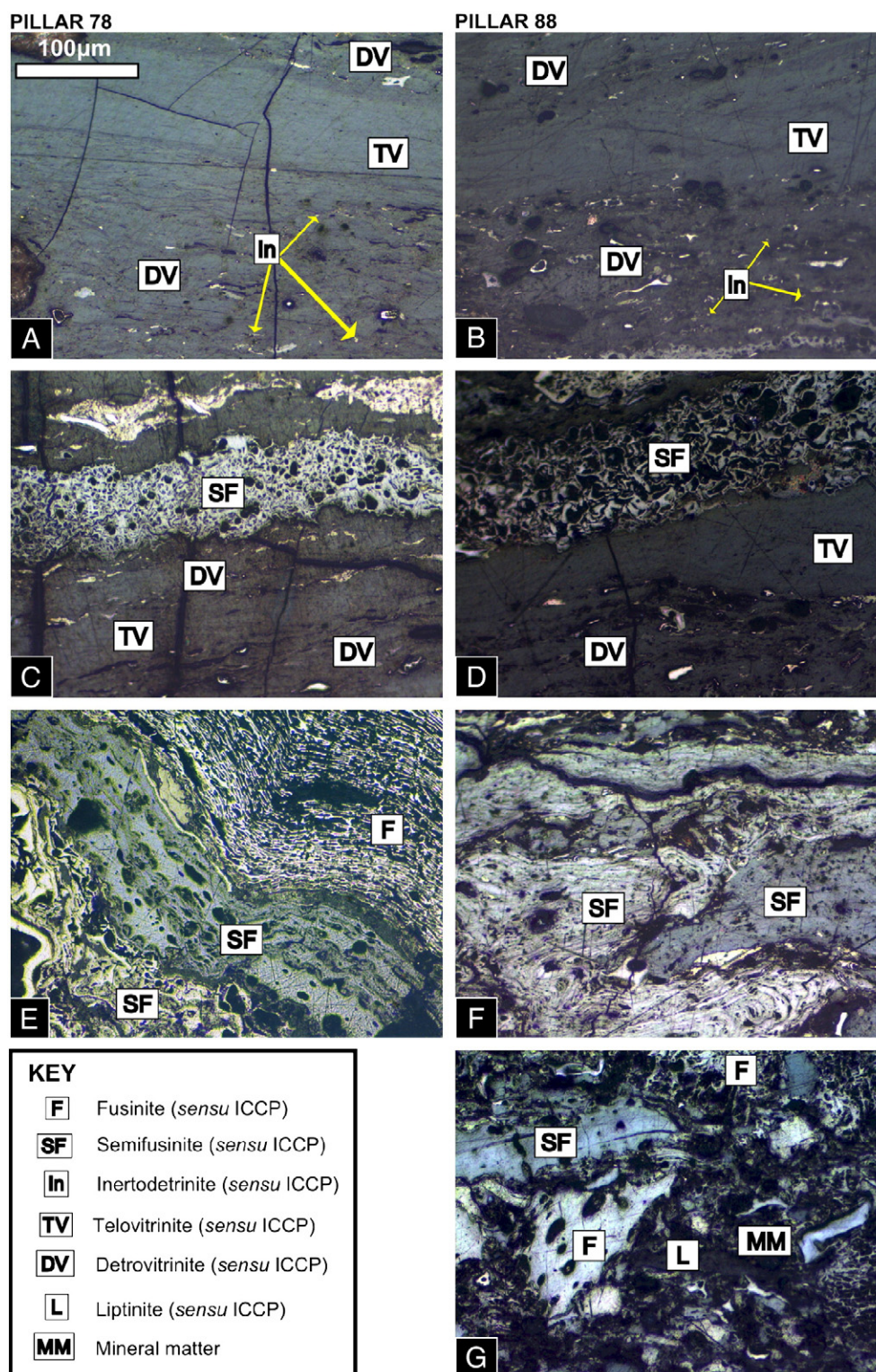


Fig. 6. Plate showing observed variation in inertinite distribution in both coal pillars. Scale bar in A corresponds to 100 μm and is the same for all images. A and B = Alternating detrovitrinite and telovitrinite layers with microscopic inertinite in the detrovitrinite layers. As seen in 78 LU1, LU7 and 88 LU3, LU5 (Figs. 3 and 4). C and D = Alternating detrovitrinite and telovitrinite layers containing larger pieces of charcoal (semifusinite) and scattered microscopic charcoal as seen in 78 LU4–6, LU9 and 88 LU1 (Figs. 3 and 4). E and F = Macroscopic charcoal horizons seen in pillar 78 LU2, LU3, LU8, LU10 and pillar 88 LU2, LU4, LU7. G = Scattered inertinite macerals throughout sapropelic lithotype units (LU2, LU4 and LU6) in pillar 88. This texture and petrographic composition is not seen in any lithotype units in pillar 78.

lithotype units containing alternating telovitrinite and detrovitrinite layers (from single to multiple fields of view in thickness) (Fig. 3). (i) Detrovitrinite layers with scattered liptinite, mineral matter, and microscopic inertinite (<180 μm *sensu* Scott, 2010) (LU1 and LU7; Figs. 3 and 6A). (ii) Detrovitrinite layers with larger, scattered pieces of macroscopic fusinite and semifusinite alongside the smaller inertinite components (e.g. LU4–LU6, LU9; Fig. 3 and 6C). (iii) Charcoal horizons with laterally continuous layers of large discrete clasts of fusinite and semifusinite (LU2 (e.g. Fig. 7), LU3, LU8, LU10; Figs. 3 and 6E) as opposed to a single continuous band of charcoal.

There are 11 charcoal horizons in total in four lithotype units, with 1–4 horizons per lithotype unit (Fig. 3). Clast sizes range from >0.5 mm to 14 mm. Lithotype units LU2 and LU3 contain more semifusinite than fusinite (Fig. 5), whereas LU8 and LU10 contain more fusinite than semifusinite (Fig. 5).

3.3. Inertinite distribution and abundance in pillar 88

The 88 pillar can be divided into seven visually distinct lithotype units macroscopically (Fig. 4). These are bright (LU3, LU5), dull (LU2, LU4, LU6) and bright banded (LU1 and LU7).

Petrographic results from the lithotype unit analysis are illustrated in Fig. 5. Inertinite is present in varying abundances throughout the coal pillar, ranging from 3% to 45% in different lithotype units (Fig. 5) with a whole pillar average of 48% mmf basis (st. dev. = 2.3; Table 1). The microscopic variation in inertinite distribution can be divided into four categories. The first three are the same as the inertinite distribution patterns seen in pillar 78 (i.e. 88 LU1, LU3, LU5, LU7; Fig. 4 and 6B, D) and the fourth is unique to pillar 88 (i.e. LU2, LU4, LU6; Fig. 4 and 6G). Lithotype units in this fourth category contain no alternating telovitrinite and detrovitrinite layers, are generally vitrinite poor (20–28%; Fig. 5) and contain scattered inertinite macerals (41–45%) in every field of view (Fig. 6G). The most abundant inertinite macerals are semifusinite (8–14%) and inertodetrinite (9–15%) with minor fusinite (2–8%), and high reflecting secretinite (3–8%). These lithotype units are also rich in mineral matter (19–26%, kaolinite and quartz, confirmed by XRD) and macerals are commonly rounded.

There are 26 charcoal horizons in three lithotype units, LU2 (16 horizons), LU4 (8 horizons) and LU7 (2 horizons) (Fig. 4 and 6F) with a maximum clast size of 8 mm (LU2). Charcoal horizons are laterally continuous layers with large discrete clasts of fusinite and semifusinite as opposed to a single continuous band of charcoal and they contain more semifusinite (7.5–15%) than fusinite (5–7%; Fig. 5). Lithotype units LU3 and LU5 contain less inertinite (3–10%; Fig. 5) than those containing charcoal horizons (LU2, LU4, LU7).

4. Discussion

4.1. Comparison to previous published petrographic work

The randomly sampled coal pillars used in this study demonstrate an approach to interpreting wildfire history over a short time interval in the Late Permian Period. Pillar 78 contains a mean inertinite content of 29.8% mmf basis (st. dev. = 1.3; Table 1) which is comparable to previously published work (33%) (Pakh and Artser, 2003). Pillar 88 contains far more inertinite (48% mmf basis (st. dev. = 2.3; Table 1)) than documented by Pakh and Artser (2003) (22%). This discrepancy may indicate either a record of more fire events or a greater volume of charcoal produced during fire events for the time interval represented by the pillar compared to the totality of seam 88. The Pakh and Artser (2003) data represent a summary of exploration data collected over many years and therefore are likely to be representative of the seams as a whole, however, their analysis is on crushed coals which, unlike *in situ* coal pillars, do not retain their inertinite distribution and therefore cannot be used in this type of study to interpret wildfire history.

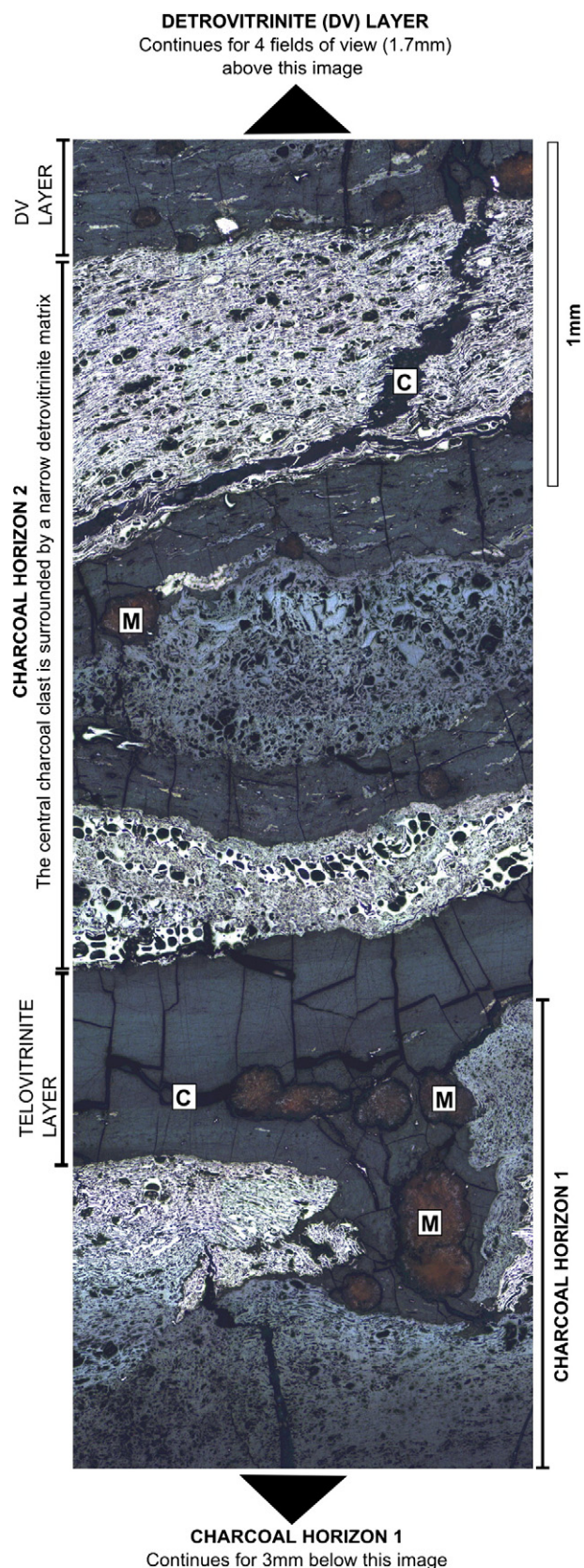


Fig. 7. Montaged images (36 in total) showing a representative 1.5 mm by 3.75 mm section of coal pillar 78 LU8 (Fig. 3) which contains two charcoal horizons (labelled 1 and 2). These charcoal horizons persist laterally across the block. The central charcoal clast in charcoal horizon 1 is surrounded by a matrix of detrovitrinite as is typical for the clasts in the charcoal horizons. The detrovitrinite matrix is always less than one FOV in thickness (often much less) in striking contrast to detrovitrinite layers such as that which extends for 1.7 mm at the top of the image shown. m = mineral matter; c = crack.

4.2. Peat-forming environments

The peats were formed in extensive mire systems (Gore, 1983) that existed for considerable periods of time, producing coals often in excess of 10 m thick (Fig. 2A). The sedimentological setting of the coal-bearing sequence suggests that these mires were within a floodplain setting between avulsing deep (18–50 m) fast flowing channels (Davies et al., 2010). Angaran peat-forming vegetation was dominated by Cordaitalean trees e.g. *Cordaitea* and *Ruffordia* (Krassilov, 2000; Meyen, 1982; Rees et al., 2002) belonging to the Angaran province (Chaloner and Meyen, 1973). In the study area, this is shown by abundant plant impressions of leaves observed on inter-seam sediments (VH and ACS personal observations). Permineralised gymnosperm axes show distinctive growth-rings (ACS personal observations), indicating a seasonal climate (Chaloner and Creber, 1973).

Pillar 78 is low in ash (<7.5% d basis) and sulphur (<1.3% daf basis) (Table 2), suggesting formation in an ombrotrophic, rain-fed, peat-forming environment (Moore, 1987; Scott, 1989b). These form thick, zoned peats with domed topography (Moore, 1987; Scott, 1989b) although this morphology was not observed in the field.

Pillar 88 contains some lithotype units (LU2 and LU4) that have liptinite (sporinite) contents >10% (Fig. 5) and are therefore classed as sapropelic (Cook and Sherwood, 1991). Those rich in sporinite are termed canal coals which form in freshwater lakes (Taylor et al., 1998). The sapropelic lithotype units (LU2, LU4) are interspaced with bright and banded lithotype units (LU3, LU5, LU7) which have lower ash (7.16–17.6%) and liptinite contents (1.5–3.3%). The sapropelic lithotype units may represent small mire lakes on the peat surface of an ombrotrophic mire, similar to that illustrated in Fig. 9 of McCabe (1984).

4.3. Interpretation of wildfire type and occurrence in pillar 78

Charcoal is present in all ten lithotype units in pillar 78 (ranging from 3 to 59%; Fig. 5) thus providing evidence for wildfire occurrence throughout the formation of the coal pillar. Pillar 78 has a total mean inertinite content of 29.8% mmf basis (st. dev. = 1.3; Table 1) which suggests that there were either many fire events producing large quantities of charcoal or a high fire frequency in this mire environment during the Late Permian. This inertinite content is much higher than observed for modern peat-forming environments (~4.3% mmf) see Glasspool and Scott (2010).

The ten lithotype units microscopically all contain repeating alternating detrovitrinite and telovitrinite layers. The detrovitrinite layers contain inertinite macerals distributed either as, (1) scattered microscopic inertinite (LU7; Fig. 6A), (2) a combination of scattered macroscopic fusinite and semifusinite amongst smaller inertinite components (Fig. 6C) (3) charcoal horizons (large fusinite and semifusinite pieces (LU2, LU3, LU8 and LU10); Fig. 6E; Fig. 7). This variation of components in detrovitrinite layers represents wildfire events of varying size, proximity and type throughout the formation of this 2300 mm *in situ* coal pillar.

4.3.1. Evidence for crown fires

Crown fires combust living vegetation from both canopy and understorey trees (Davis, 1959; Scott and Jones, 1994), at high temperatures (Pyne et al., 1996) around 800–900 °C (Pyne et al., 1996). Charring temperatures >600 °C can cause fragmentation of charcoal (Scott and Jones, 1991) and therefore crown fires may be identified in the sequence by the presence of small, high reflecting charcoal. This charcoal may have been windblown or water transported (Clark, 1988; Clark et al., 1998; Ohlson and Tryterud, 2000; Patterson et al., 1987; Scott and Glasspool, 2007). Microscopic charcoal (<180 µm but more commonly <20 µm) is generally interpreted as the windborne size fraction from regional, particularly

crown fire events within 20–100 km of the fire source (Clark et al., 1998; Clark and Patterson, 1997; Collinson et al., 2007; Conedara et al., 2009; Lynch et al., 2004; Ohlson and Tryterud, 2000; Peters and Higuera, 2007; Pitkänen et al., 1999; Power et al., 2010; Scott, 2002; Scott et al., 2000a). High reflecting inertodetrinite (<10 µm) is present in all lithotype units in small amounts (0.2–5%; Fig. 5) in detrovitrinite layers, which suggests charcoal production and dispersal from frequent background, crown fire events.

The telovitrinite layers occurring between detrovitrinite layers (all lithotype units) either contain no inertinite macerals or occasional, widely spaced, scattered inertodetrinite. The presence of inertodetrinite in some of the telovitrinite layers confirms that these layers cannot be single compressed plant organs. These alternating detrovitrinite and telovitrinite layers are therefore interpreted to represent background, regional fire events followed by periods without fires enabling a build-up of fuel as seen in modern fire events (e.g. Pierce et al., 2004).

4.3.2. Charcoal horizons: Surface fires and relative fire temperature

There are 11 charcoal horizons in the coal pillar (Fig. 3) that contain pieces of macroscopic charcoal (Fig. 7) observed in lithotype units LU2, LU3, LU8 and LU10. These charcoal horizons are considered to represent charred vegetation from surface fire events as these produce the most charcoal (Scott, 2010) and burn both living and dead plant material (derived from both surface and canopy) at low temperatures (Scott, 1989a; see data compilation in Scott, 2000; Scott and Jones, 1994; McParland et al., 2009). Low temperature charcoal may be represented in coal as semifusinite (Jones et al., 1991, 1993; Scott, 2000; Scott and Glasspool, 2007; Scott and Jones, 1994). Semifusinite is the most abundant inertinite maceral in LU2 and LU3 (13–29%; Fig. 5) which suggests that these charcoal horizons formed in cool temperature fire events. Furthermore, fusinite and semifusinite pieces in charcoal horizons in LU2 and LU3 show gradational reflectance (e.g. Fig. 8A, B). This represents partially charred material, where the fire may burn quickly due to short fire duration and/or high levels of vegetation moisture. However, in the upper inertinite-rich lithotype units (LU6, LU8, LU9 and LU10) high reflecting (qualitative) fusinite is the dominant inertinite maceral (18–39%), followed by semifusinite (13–18%) suggesting higher temperature fires during this period of peat formation.

The macroscopic charcoal in these horizons may have been transported locally by wind under particular conditions (e.g. Tinner et al., 2006), but more commonly by water transport through overland flow (Komarek, 1973; Scott, 2009, 2010; Scott et al., 2000a). The occurrence of several charcoal horizons in a sequence (as seen here) may represent seasonal fire events whereas large catastrophic fire events would be represented by single, thick charcoal deposits (Scott and Jones, 1994) which are not observed in either coal pillar.

4.3.3. Evidence for other small fire events

A range of charcoal sizes including macroscopic charcoal (not in horizons) is observed in LU4–6 and LU9 (Fig. 3). This charcoal may represent windblown or water transported larger pieces (as documented in modern fires by Scott et al., 2000a and Tinner et al., 2006) from more local fire events (Scott, 2010).

4.4. Interpretation of wildfire type and occurrence in pillar 88

Charcoal is present in all seven lithotype units in varying amounts (3%–56%) with a pillar average of 48% mmf basis (st. dev. = 2.3; Table 1), which is higher than pillar 78 (average of 29.8% mmf basis (st. dev. = 1.3; Table 1)). This provides evidence for frequent wildfire occurrence during the formation of this coal pillar. A summary of the variation in inertinite distribution between lithotype units in pillar 88 is given in Fig. 4.

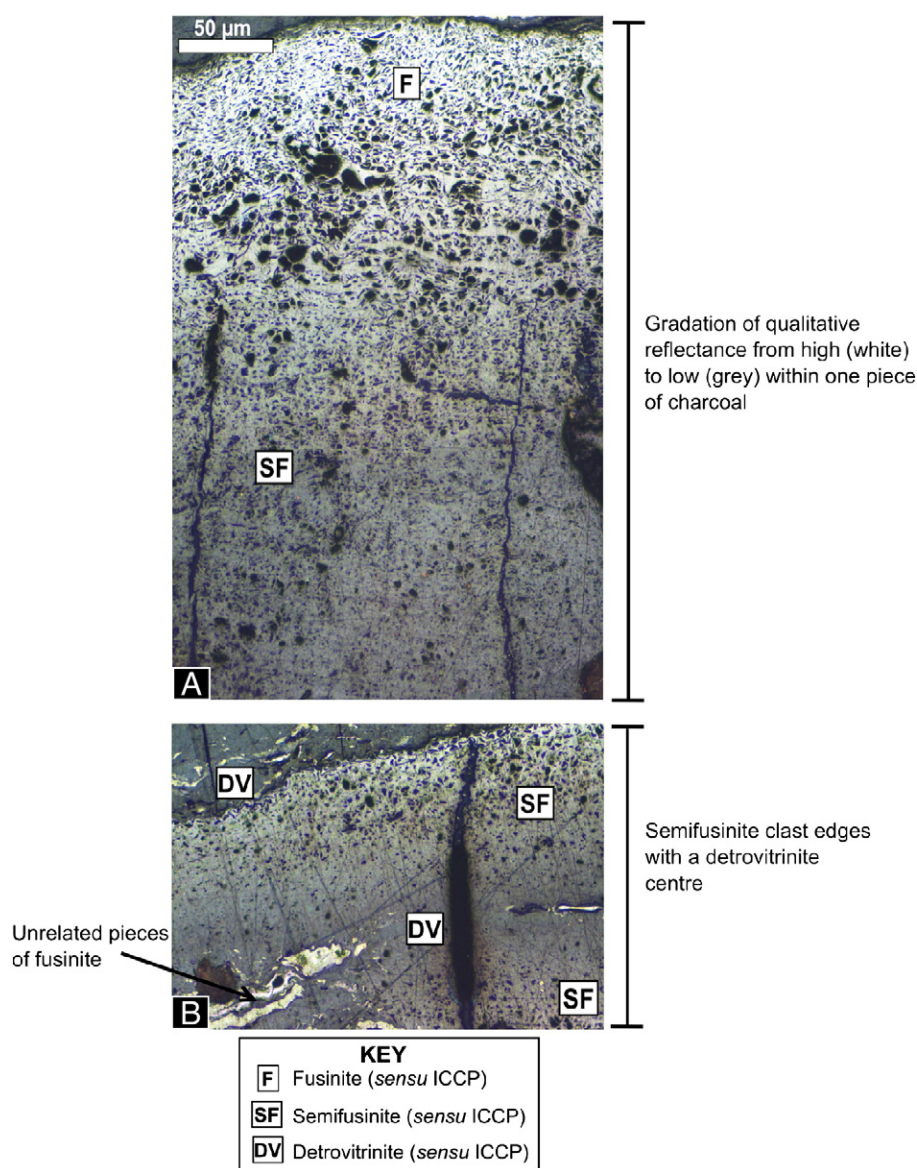


Fig. 8. Partially charred tissue showing gradational qualitative reflectance (pillar 78 LU2). Scale bar in image A corresponds to 50 μm and is the same for both images. A = shows a gradation in reflectance on a single surface and could represent a twig that has been partially buried prior to charring. B = shows a transition in reflectance from semifusinite to vitrinite to semifusinite, representing an entire charred margin suggesting that the twig may have been charred in growth position.

Four of seven lithotype units studied in pillar 88 microscopically resemble those in pillar 78 and contain repeating alternating detrovitrinite and telovitrinite layers (Fig. 4). The detrovitrinite layers contain inertinite macerals distributed either as, (1) scattered microscopic inertinite (LU3, LU5; Fig. 6B), (2) a combination of scattered macroscopic fusinite and semifusinite amongst smaller inertinite components (LU1; Fig. 6D) (3) charcoal horizons (large fusinite and semifusinite pieces (LU2, LU4 and LU7); Fig. 6F). In addition, lithotype units (LU2, LU4, LU6) contain mixed charred and uncharred components in a liptinite and mineral rich background with little vitrinite (Fig. 6G). This variation of inertinite distribution between lithotype units represents wildfire events of varying size, proximity and type throughout the formation of this 3600 mm *in situ* coal pillar.

4.4.1. Evidence for crown fires

Lithotype units LU3 and LU5 contain the least amount of charcoal (2% and 10% respectively; Fig. 5) in thin detrovitrinite layers (<425 μm wide) containing widely scattered inertodetrinite (2–3%),

liptinite, mineral matter and small fusinite and semifusinite pieces. The majority of each lithotype unit is telovitrinite (70–83%). This suggests intervals without local fire events and only infrequent background regional crown fire events.

Lack of large charcoal particles (>200 μm) in these lithotype units (LU3, LU5) also suggests that this material is windblown from a regional fire source (Clark et al., 1998). There is no low reflecting inertodetrinite in pillar 88 suggesting an origin from high temperature crown fire events.

Sapropelic lithotype units (LU2, LU4) contain large quantities of inertodetrinite (9–15%) and macrinite (<50 μm in size). These macerals are scattered in every field of view throughout these lithotype units and may represent an elevated background regional fire signal as observed in modern charcoal distributions by Power et al. (2010). Alternatively, charring temperatures >600 °C can cause fragmentation of charcoal (Scott and Jones, 1991) so this highly reflecting inertodetrinite and macrinite may represent fragmented, water transported, high temperature charcoal from regional crown fire events.

4.4.2. Evidence for multiple local surface fire events

There are 26 charcoal horizons present in three lithotype units, two of which are sapropelic (LU2 16 horizons, LU4 8 horizons; Fig. 4) and one which is banded (LU7; Fig. 4). All charcoal horizons have particle sizes of >0.5 mm. This charcoal may have been produced in low intensity (Clark et al., 1998; Ohlson and Tryterud, 2000; Scott, 2010), low temperature (as shown by the dominance of semifusinite 7.5–16%; Fig. 5) surface fires (as seen in pillar 78).

The base of LU7 is marked by a charcoal horizon, representing a surface fire which suggests that an ombrotrophic peat-forming environment (terminating LU6; Fig. 4) must have established in order to produce litter that was then charred, or it represents material washed in from a separate fire event from outside of the peat-forming area. The majority of charcoal in this horizon is partially charred (Jones et al., 1993) material (e.g. Fig. 8A, B) and as with similar material in pillar 78 it may have formed as a result of the fire burning quickly or the plants having high levels of moisture.

Discrete clasts of fusinite and semifusinite in charcoal horizons are observed in sapropelic lithotype units LU2 (16 horizons) and LU4 (8 horizons) which are likely to represent influxes of charred material from surface fire events which settle out in the mire lake environment. These pieces of charcoal are found within horizons which persist laterally across the block. This suggests limited reworking within the mire lake.

4.4.3. Evidence for other small fire events

The presence of semifusinite in six of seven lithotype units (3–16%; Fig. 5) represents charcoal formed in low temperature, low intensity, surface fire events, <400 °C (Jones et al., 1997; Scott and Glasspool, 2007; Scott and Jones, 1994; Scott et al., 2000a).

Macroscopic charcoal is completely scattered throughout lithotype units LU2, LU4 and LU6. The maceral associations in these lithotype units include scattered inertinite (41–45%; Fig. 5), uncharred liptinite (4–16%; Fig. 5) and mineral matter (19–26%). The combination of charred and uncharred material is likely to be a result of a portion of biomass being charred and producing charcoal during the fire event and an amount remaining uncharred (Nichols et al., 2000; Scott, 2010). These components may later be transported together and mixed in the same lithotype unit producing the scattered distribution in the coal pillar.

4.5. Recognising ground fires in coal pillars

Ground fires occur at lower temperatures than surface or crown fires (250–300 °C) (Pyne et al., 1996; Usup et al., 2004). These fires smoulder instead of producing a flame and can last from days to years with a slow spread rate of 1–50 mm per hour (Rein et al., 2008). This fire type can be ignited by canopy or surface fires (Davis, 1959) but ignition in peat is dependent on the moisture content (Rein et al., 2008).

A charred peat surface would be represented by a continuous band (Cohen et al., 1987) of charred material (fusinite or semifusinite) whereas the charcoal horizons in the coal pillars studied are composed of large clasts of charcoal that are surrounded by vitrinite matrix and therefore represent transported material and not charred peat. There is no evidence of ground fires and no charred peat surface or layer in either coal pillar.

4.6. Calculating fire return intervals using charcoal horizons

Where discrete charcoal horizons with large clasts occur there is potential to reconstruct fire return intervals (FRI) from coal pillars. There are a wide range of peat accumulation rates (0.2 mm/a⁻¹ (Aaby and Tauber, 1975) to 2 mm/a⁻¹ (Taylor et al., 1998)) and peat to coal compaction ratios (1:1 to 30:1) (see Ryer and Langer (1980); Winston (1986)) which can be used to represent extremes in time intervals of original peat formation. Most likely or mid range values (accumulation 1 mm/a⁻¹ and compaction 7:1) are also used (Table 3). Modern peat-forming systems, from which accumulation rates are derived, contain relatively little charcoal compared to those of the Late Palaeozoic (Glasspool and Scott, 2010). Where discrete charcoal horizons occur (and might represent just one fire hence a very short time interval) this will affect both accumulation rate and compaction ratio (as charcoal compaction differs from that of peat). One possible approach to take account of these issues is to use peat thickness with and without charcoal thickness to obtain end member values of the time interval represented by the lithotype unit.

This approach has been applied to two lithotype units (78 LU2 and 88 LU7) representing ombrotrophic mire depositional settings but with variation in both charcoal horizon occurrence (78 LU2 4 horizons, 88 LU7 2 horizons) and cumulative horizon thickness in the coal pillar (6.2 mm and 3 mm respectively; Table 3) to demonstrate the range in potential fire return intervals in ombrotrophic mire depositional settings within these coal pillars. Mid value FRI are between 7 years (extremes 0.5 to 143 years) for 78 LU2 to 70 years (extremes 5–1550 years) for 88 LU7.

4.7. Comparison to modern fire return intervals

Comparing the calculated FRI values to modern peat-forming environments is not straightforward. Modern examples of FRI range from 200 to 750 years in subtropical peat-forming environments (Spackman et al., 1976) to 200–1100 years for *Sphagnum* bogs and heathlands (Innes et al., 2004; Muller et al., 2008; Stähli et al., 2006) to 80–475 years in treed boreal peatlands (Ohlson et al., 2006; Turetsky and St. Louis, 2006) and 230–600 years for subalpine peatlands (Stähli et al., 2006). Furthermore, this range of FRI may not always represent the natural wildfire frequency as the human impact on fire regimes is not fully understood (e.g. Flannigan et al., 2009) and it is difficult to distinguish between anthropogenic and natural fires

Table 3
Calculated fire return intervals for two lithotype units in pillars 78 (LU2) and 88 (LU7). These lithotype units represent comparable environments of deposition in ombrotrophic mire settings but with variation in both number of charcoal horizons and cumulative charcoal horizon thicknesses. Peat accumulation rates represent the full range in all peat-forming environments, 1 mm/a⁻¹ is highlighted as climate during the Permian in Siberia was temperate (Ziegler, 1990) and this value represents the most likely accumulation rate in a temperate peat-forming environment. The values in bold represent 7:1 compaction ratios which is the median value used in previous published work (i.e. Ryer and Langer, 1980; Winston, 1986). Fire return interval is calculated by dividing the duration of peat formation by the number of charcoal horizons.

LU	LU thickness	Charcoal thickness	Number of charcoal horizons	Peat accumulation rate	Corresponding peat thickness median compaction ratio 7:1 (range 1:1–30:1)	Duration of peat formation	Fire return interval (FRI)
78 LU2	10 mm	6.2 mm	4	0.2 mm/a ⁻¹	26.6 mm (3.8–114 mm)	133 years (19–570 years)	33 years (5–143 years)
				1 mm/a ⁻¹	26.6 mm (3.8–114 mm)	26.6 years (3.8–114 years)	7 years (1–29 years)
				2 mm/a ⁻¹	26.6 mm (3.8–114 mm)	13.3 years (1.9–57 years)	3 years (0.5–14 years)
				0.2 mm/a ⁻¹	140 mm (20–600 mm)	700 years (100–3000 years)	350 years (50–1550 years)
88 LU7	23 mm	3 mm	2	1 mm/a ⁻¹	140 mm (20–600 mm)	140 years (20–600 years)	70 years (10–300 years)
				2 mm/a ⁻¹	140 mm (20–600 mm)	70 years (10–300 years)	35 years (5–150 years)

(Bowman et al., in press; Scott et al., 2000b). It is therefore difficult to compare values from modern and ancient peat-forming systems, especially in deep time when the peat-forming vegetation is long extinct. However, allowing for this caveat the mid range FRI values calculated for two lithotype units from these Late Permian coal pillars suggest shorter fire return intervals than seen in modern peat-forming environments.

4.8. Comparisons between charcoal amount in pillars 78 and 88

Our data suggests that while the two coal pillars contain differing amounts of charcoal their wildfire histories are relatively similar. This variation in quantity of charcoal between pillar 78 (mean of 29.8% (st. dev. = 1.3; Table 1)) and pillar 88 (48% (st. dev. = 2.3; Table 1)) could be related to the nature of the fuel load, the spread and temperature of the fire, and resulting charcoal production and nature of the transport–depositional system.

5. Conclusions

There is currently no universal standard method for petrographic analysis of *in situ* coal pillars. Traditional petrographic techniques for maceral analysis and coal characterisation use crushed coals but these do not retain original spatial or temporal context and therefore cannot be used for wildfire interpretation. We consider that studies of *in situ* coal pillars, such as documented herein, are essential for research into palaeo-wildfire type, occurrence and frequency.

The two *in situ* coal pillars in this analysis (from seams 78 and 88) represent coals formed in different environments of deposition within the peat-forming system. The low ash (<7.5% d basis) and low sulphur (<1.3% daf basis) content of pillar 78 (Table 2) suggests formation in an ombrotrophic mire. In contrast the small particle size, high liptinite and low vitrinite in the two thickest lithotype units (LU2, LU4) of pillar 88 indicate sapropelic coal formed in a mire lake environment within an ombrotrophic peat-forming system. This is supported by the high ash (19–21%) and mineral matter (19–22%) contents and the mixture of maceral components.

Wildfire charcoal is present in varying amounts in all lithotype units in both pillars averaging 29.8% in pillar 78 and 48% in pillar 88 (mmf basis). For seam 78 this value is similar to previous results from crushed coals (Pakh and Artser, 2003) but, our sample from seam 88 contains more inertinite (48%) than documented in literature (22%). Similar patterns of inertinite distribution are observed petrographically in both pillars either as, (1) microscopic charcoal (*sensu* Scott, 2010) which is scattered in detrovitrinite layers and represents a background, regional crown fire signal. (2) pieces of widely scattered macroscopic charcoal in lithotype units 78 LU4–6, LU9 and 88 LU1 (Fig. 3 and 4) which may represent waterborne or windblown pieces of charcoal transported from local fires or (3) multiple episodic horizons with macroscopic charcoal (e.g. Fig. 7; 78 LU2, LU3, LU8, LU10; 88 LU2, LU4, LU7) representing charred litter or biomass from individual, local surface fire events within the peat-forming environment.

There are 11 charcoal horizons in pillar 78 and 26 in pillar 88. Twenty four of the twenty six charcoal horizons in pillar 88 occur in sapropelic lithotype units, LU2 and LU4. These horizons are also characterised by high mineral matter contents (19–22%), scattered inertodetrinite (7%) and uncharred cuticle. The mix of charred and uncharred fractions may represent portions of charred and uncharred vegetation from the same area transported together.

Discrete charcoal horizons in two lithotype units from each pillar which represent comparable ombrotrophic mire depositional settings but variation in both number of charcoal horizons (78 LU2 4 horizons, 88 LU7 2 horizons) and cumulative charcoal horizon thicknesses in the coal pillar (78 LU2 6.2 mm, 88 LU7 3 mm) were used to demonstrate an approach to calculating fire return intervals (FRI). Mid-range values (7:1 peat to coal compaction ratio and 1 mm/a^{−1} peat accumulation

rate) give FRI between 7 years (extremes 0.5 to 143 years) for 78 LU2 to 70 years (extremes 5–1550 years) for 88 LU7. The mid range values for these lithotype units demonstrate shorter FRI than seen in examples from modern peat-forming environments which range from 80 to 1100 years.

A record of both regional crown fires and local, surface fires is represented in these coal pillars. Despite the different depositional settings, and variations in mean inertinite content of the two seams studied, they record similar wildfire type and occurrence.

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